

Space Weather: what does it cost and how bad can it get?

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I:

Solar-flare induced disturbances in the U.S. electric grid and their economic impact

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II:

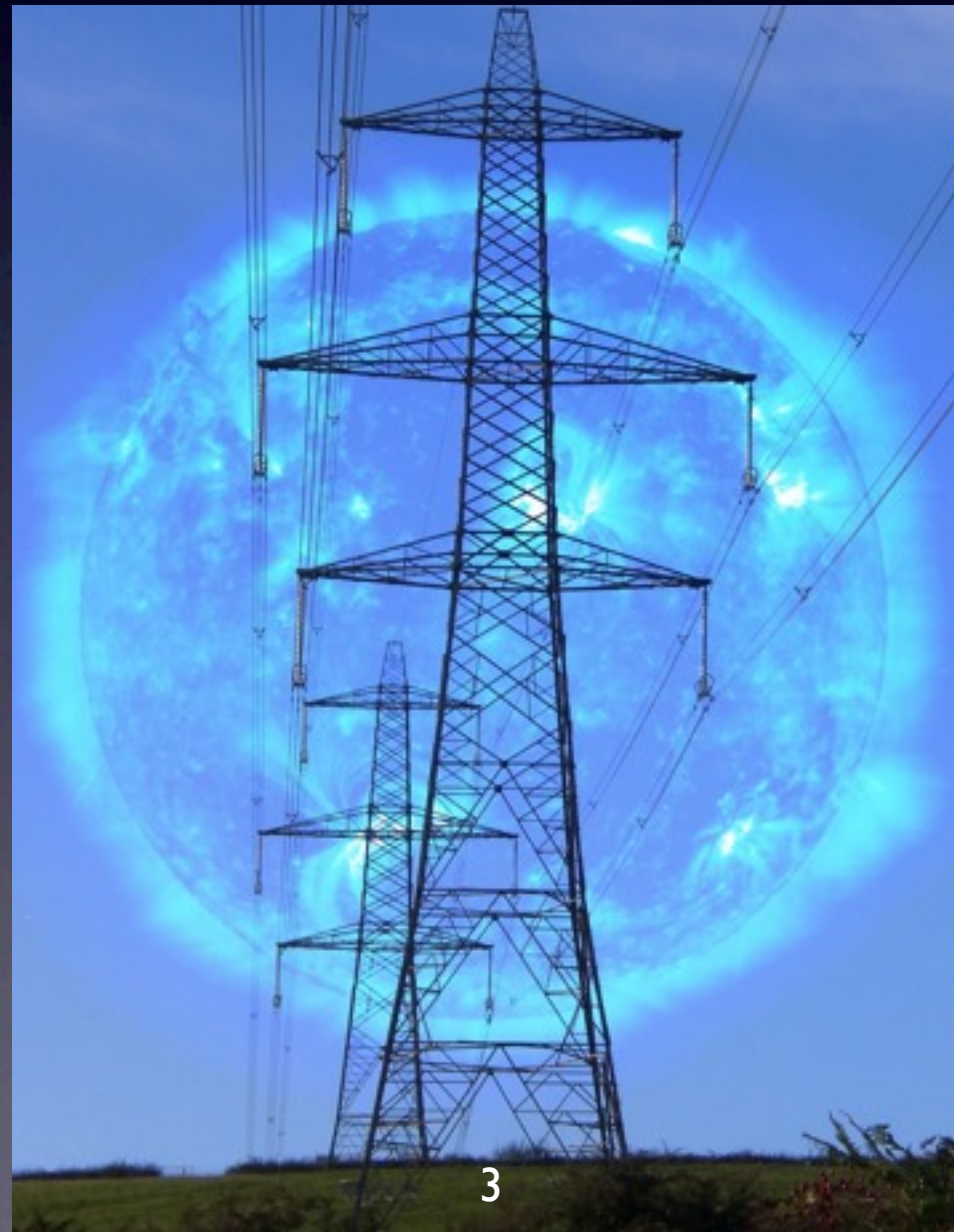
Estimating the frequency of extremely energetic solar events, based on solar, stellar, lunar, and terrestrial records

Karel Schrijver, Juerg Beer, Urs Baltensperger, Ed Cliver,
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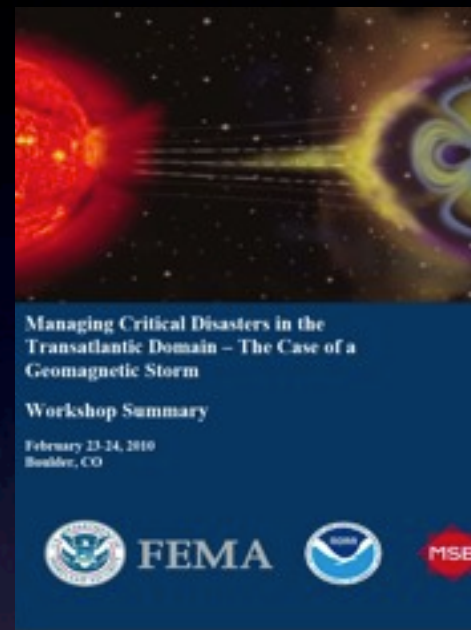


Space-weather impact studies



"[...] an estimate of \$1 trillion to \$2 trillion during the first year alone was given for the societal and economic costs of a “severe geomagnetic storm scenario” with recovery times of 4 to 10 years."

"What are the societal and economic impacts of severe space weather? [...] While this workshop, along with its report, has gathered in one place much of what is currently known or suspected about societal and economic impacts, it has perhaps been most successful in illuminating the scope of the myriad issues involved, and the gaps in knowledge that remain to be explored in greater depth than can be accomplished in a workshop. A quantitative and comprehensive assessment of the societal and economic impacts of severe space weather will be a truly daunting task [...]"



“... in many cases, both the private and public sectors do not fully understand the level of interconnectivity between various infra-structures and therefore do not grasp the extent of the space weather threat.” “If industry leaders understand the impacts of geomagnetic storms on the electrical generation and transmission system and technological equipment, they can develop plans and procedures to make systems more resilient.” “[A] geomagnetic storm can destroy large electrical transformers which are expensive and time consuming to replace. [...] New orders for replacement equipment can take up to 18 months or even longer to fulfill. If Sweden, Great Britain, and the United States all suffered transformer damage from a geomagnetic storm, it would be difficult for equipment providers to prioritize which countries should receive replacement parts.”



"The risks posed by space weather are now magnified through what some commentators have called “creeping dependency”, which means the growth of interconnect-ed systems that business and other activities rely on. [...] Therefore a space weather event could have wider regional and even global impacts: by triggering cascading failures across systems." "The ideal response to space weather risks is to build robust assets and systems that can operate through bad space weather conditions. [...] The building of robust systems will impose extra costs on business, and some measures may reduce the capacity of businesses to deliver services to customers, therefore reducing potential income. [...] This approach relies on obtaining information on space weather conditions and converting to a useful format."

Emphasis on worst case

- Media and science community alike put emphasis on “worst case scenario” - understandably, given the potential of trillions of dollars of impact,
- but space weather occurs all the time, on time scales from seconds (X-ray flares and solar energetic particles) to decades (galactic cosmic-ray modulation), from below our detection thresholds to large X-class flares and - perhaps - even larger and less frequent.
- Society is affected by more of this range than we now acknowledge, in communications satellites, navigation systems, power grids, ...



IEEE Spectrum, February 2012.

Severe space weather

- Significant societal impacts from category 5, some from 4 upward.
- Probability of “category 6” (once per century) remains subject to substantial uncertainty

Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	<u>Power systems</u> : widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. <u>Spacecraft operations</u> : may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. <u>Other systems</u> : pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).**	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	<u>Power systems</u> : possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. <u>Spacecraft operations</u> : may experience surface charging and tracking problems, corrections may be needed for orientation problems. <u>Other systems</u> : induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).**	Kp=8	100 per cycle (60 days per cycle)
Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	<u>Biological</u> : unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** <u>Satellite operations</u> : satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. <u>Other systems</u> : complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10 ⁵	Fewer than 1 per cycle
S 4	Severe	<u>Biological</u> : unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** <u>Satellite operations</u> : may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. <u>Other systems</u> : blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10 ⁴	3 per cycle
Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	<u>HF Radio</u> : Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. <u>Navigation</u> : Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2x10 ⁻³)	Fewer than 1 per cycle
R 4	Severe	<u>HF Radio</u> : HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. <u>Navigation</u> : Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10 ⁻³)	8 per cycle (8 days per cycle)

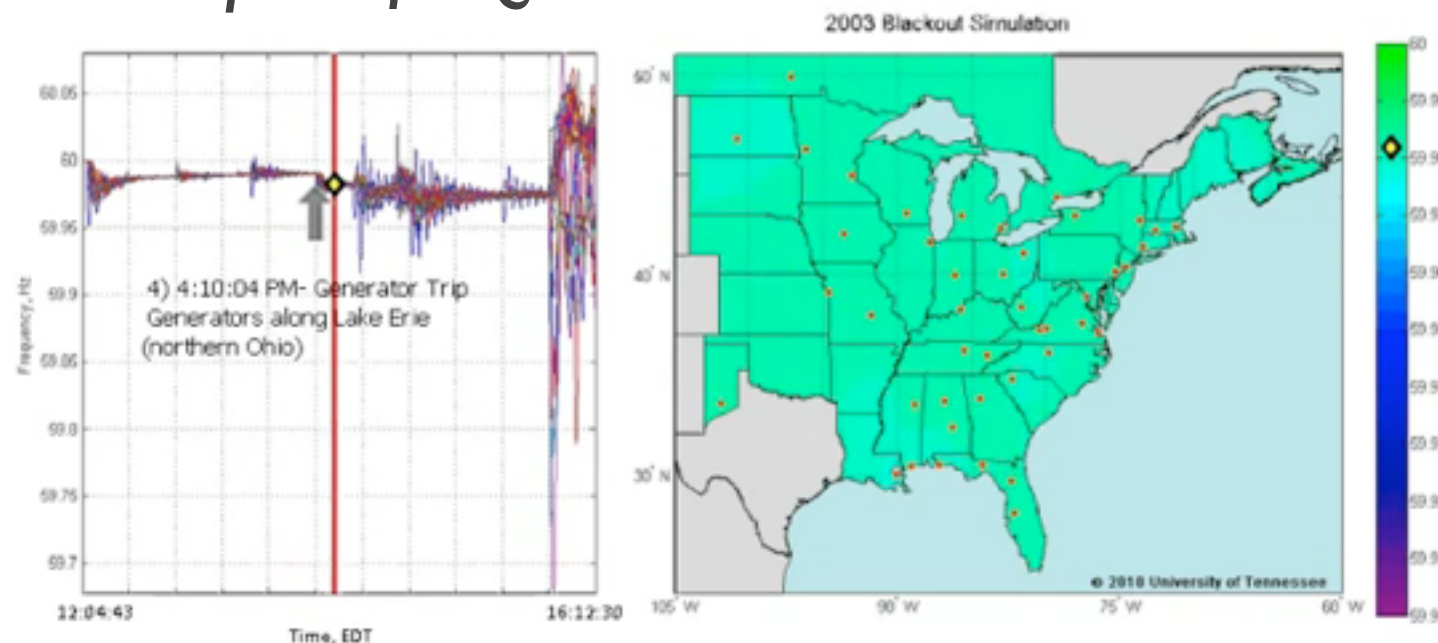
US power grid disturbances

The North American Electric Reliability Corporation (NERC) and the Department of Energy (DOE) collect and publish data on “power grid disturbances”. Reporting is mandatory for disturbances above a certain reporting threshold.

The reported disturbances include “electric service interruptions, voltage reductions, acts of sabotage, unusual occurrences that can affect the reliability of the bulk electric systems, and fuel problems,” i.e., accidental and scheduled blackouts and substantial reductions in “power quality” (PQ).

We use disturbance reports for 1216 events from 1992 through 2010.

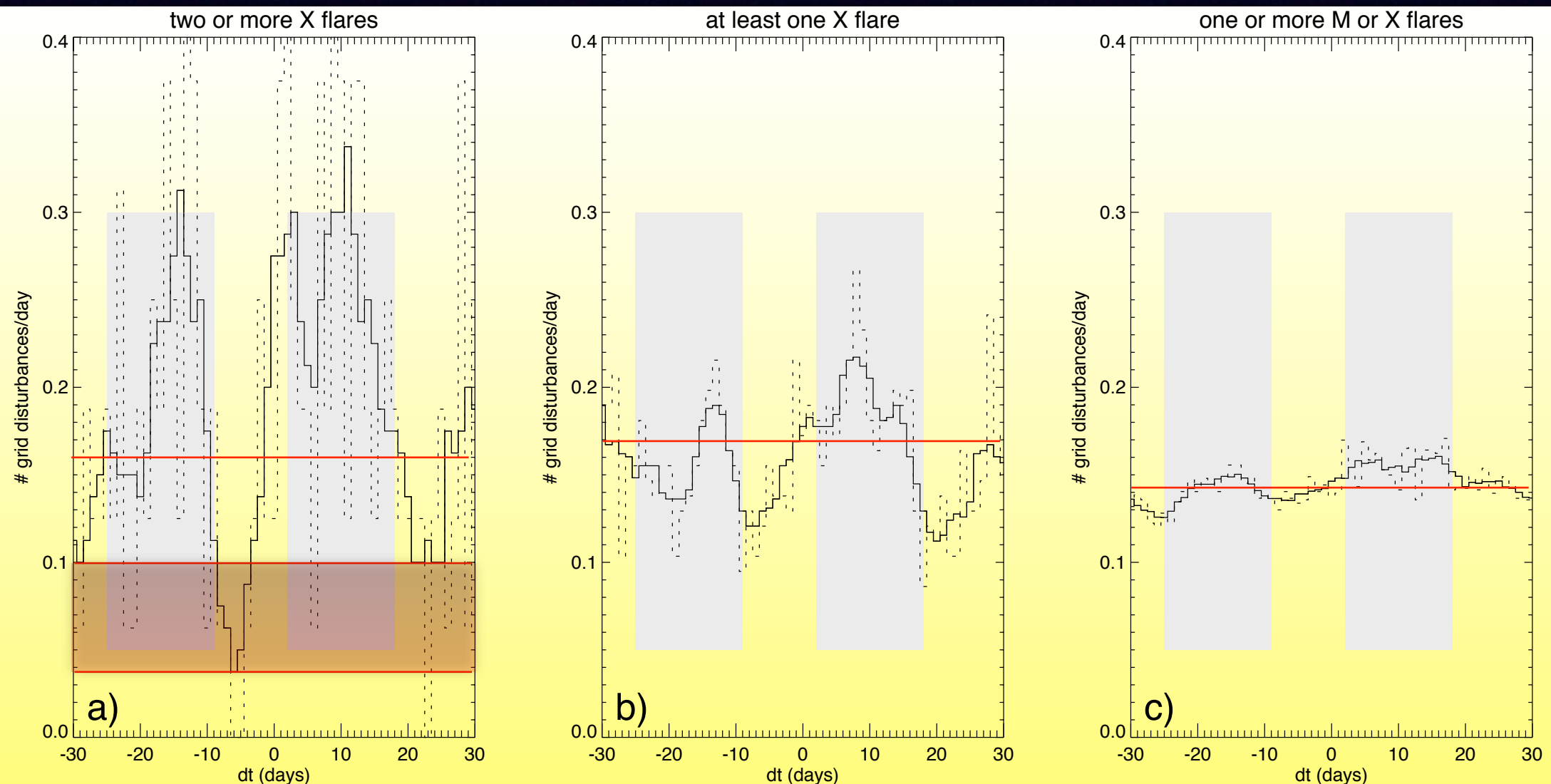
Example of PQ disturbances and blackout



<http://fnetpublic.utk.edu/>

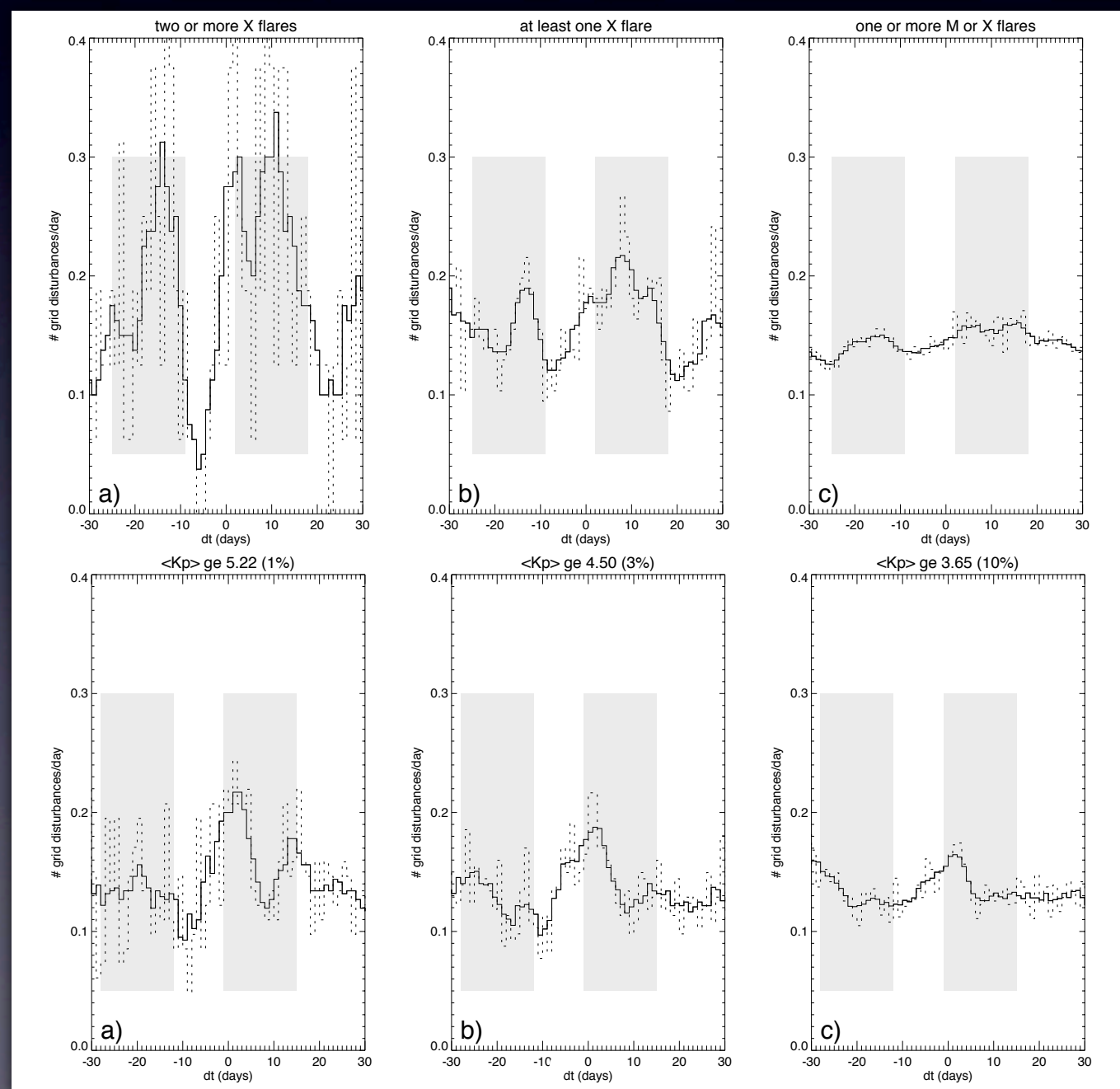
US power grid disturbances

We select all dates with major solar flares and - in a superposed epoch analysis - evaluate the grid disturbances in the days before and after such major flaring.



Correlation with flaring & Kp

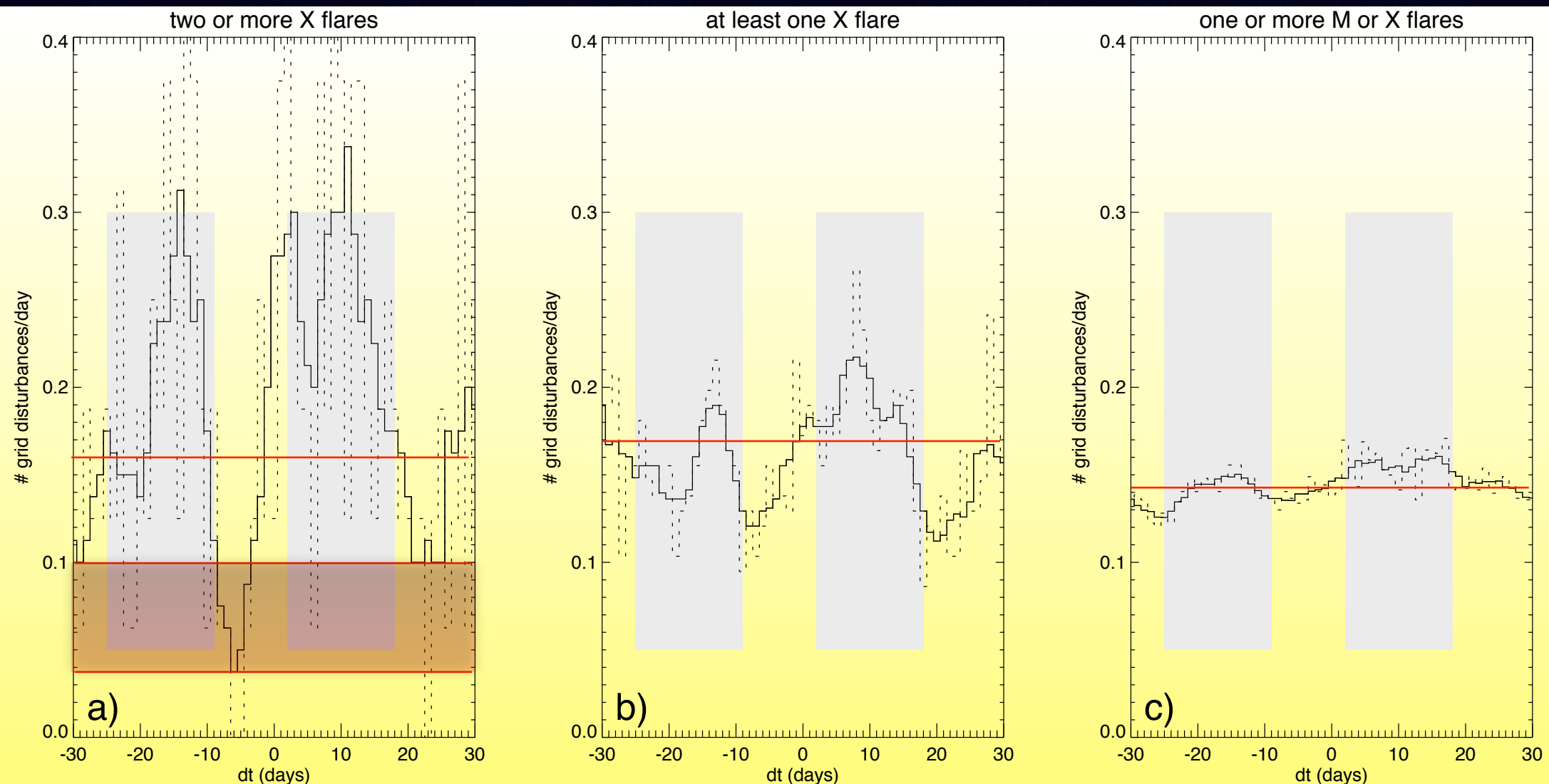
Major-flare dates and dates of unusually high geomagnetic activity (Kp index) yield comparable patterns for grid disturbance frequencies in a superposed epoch analysis.



US power grid disturbances

Except in rare cases, solar/space weather is not recognized as the cause for grid disturbances. In fact, **no disturbance was thus attributed over the 19-y period studied, either as primary cause or as contributing factor, in the NERC-DOE reports.**

This is to be contrasted to our finding that ~60 grid disturbances large enough to require reporting to DOE and NERC should be attributable to major solar flares, with at least another ~60 cases related to other space weather around the time of major flaring over that same period.



US power grid disturbances

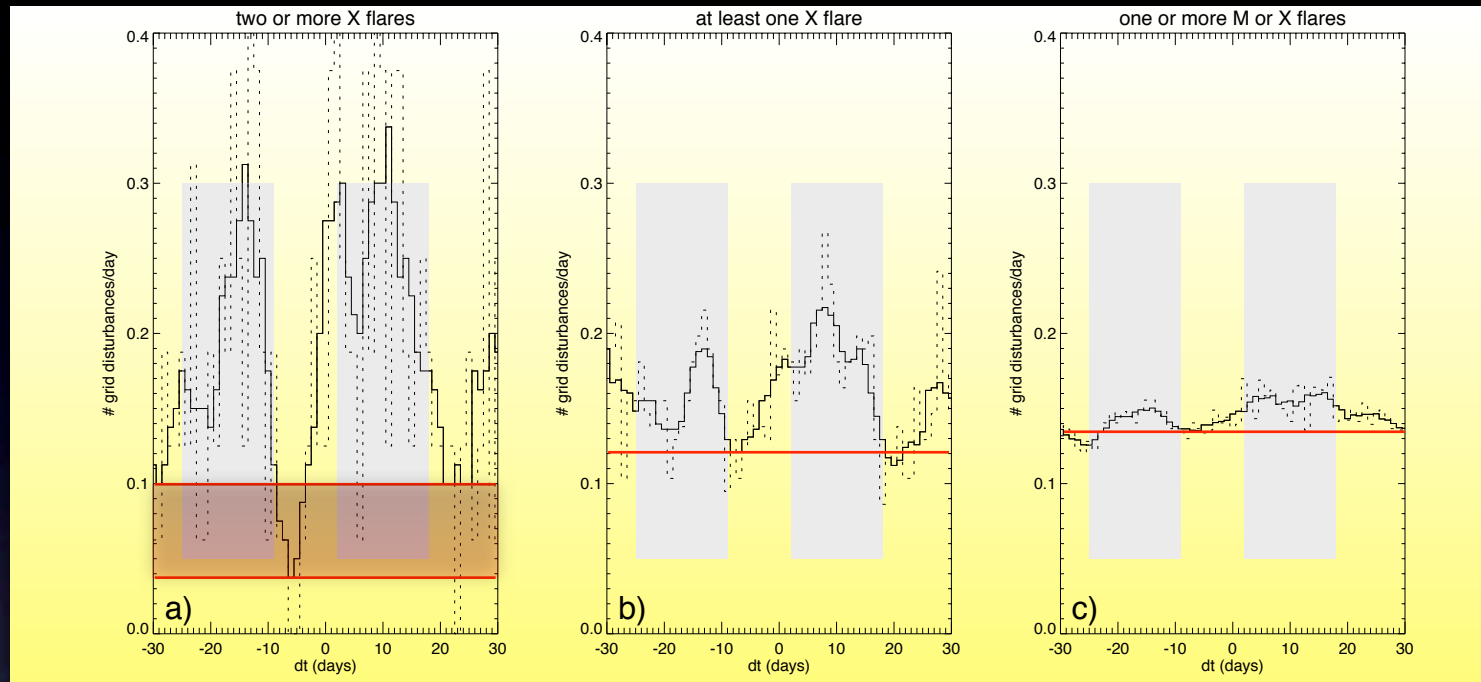
The average energy lost in the grid disturbances we studied amounts to **11-19 GWh per event**.

For a total electric power production for the U.S. in 2010, the grid disturbances attributable to major solar flaring add up to a fraction of $f_{\text{dist}} = (2.0-3.5) 10^{-6}$ of the total of about 4,000 TWh.

A plausible lower limit to the economic impact can be obtained by making the simplest assumption, namely that the economic impact equals a fraction f_{dist} of the U.S. GDP ($\sim \$14.6 10^{12}$ in 2010). With that assumption, we find an impact cost estimate between \$160M and \$280M/yr from 4.3 grid disturbances per year. The full space weather impact needs to be at least doubled to include effects from solar activity other than directly associated with M and X class flaring, which brings the range up to **\$300M to \$500M/yr**.

That simple estimate is likely substantially lower than the full economic impact. A DOE report puts the costs of "power outages and power quality disturbances" to the overall economy between \$25 billion and \$180 billion annually. A survey of the impacted sectors of industry by EPRI resulted in an annual impact of approximately \$100 B/y. If we assume that space-weather induced grid disturbances are comparable to the typical other disturbance, then the full economic impact could be as large as **\$4 billion per year**.

US power grid disturbances

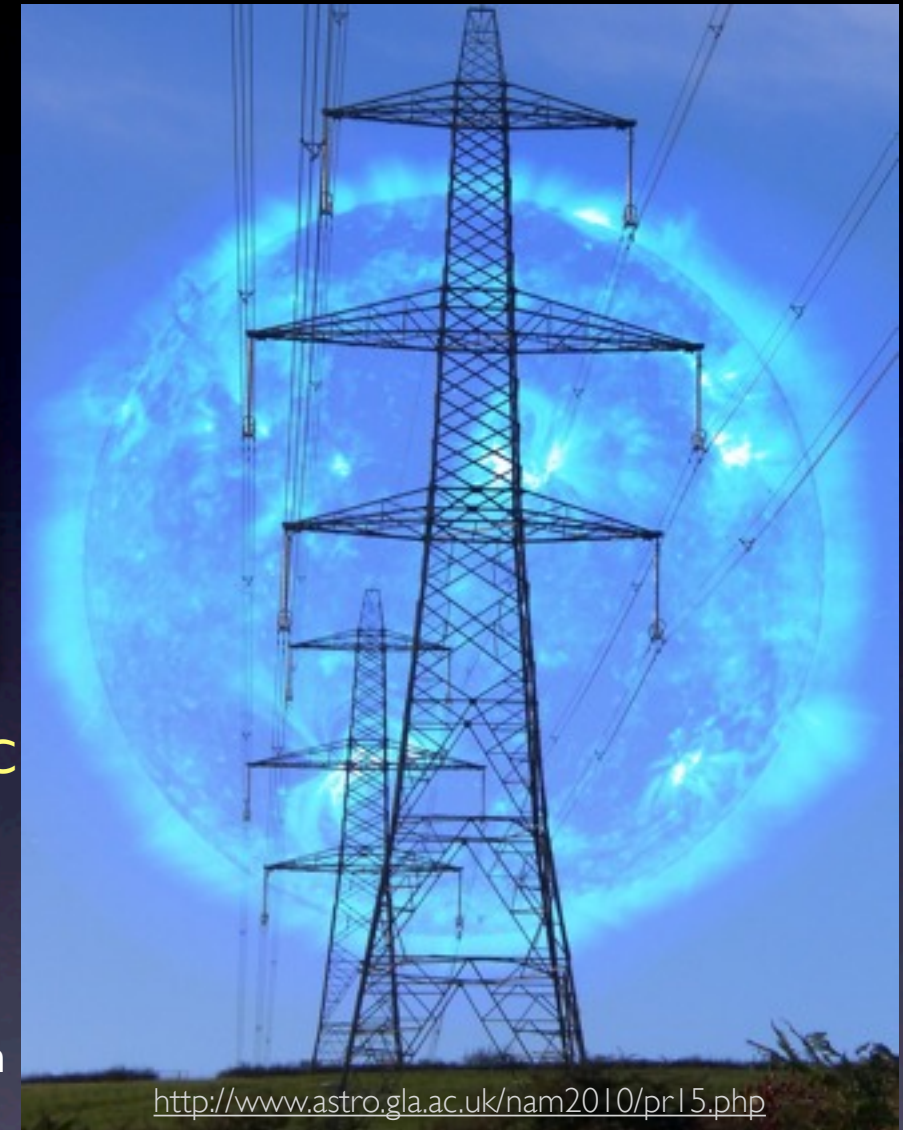


Non-catastrophic disturbances in the US power grid [reported to & by NERC & DOE] occur regularly subject to “normal” space-weather conditions:

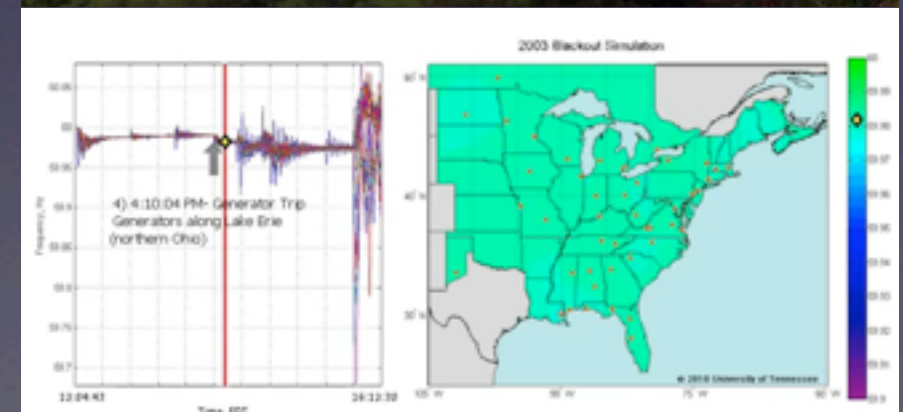
The frequency of disturbances in the U.S. electric grid from 1992 through 2010 is enhanced by at least 7% for ~18d after an M-class flare or larger, by ~25% after days with at least one X-class flare, and by almost a factor of two after days with two or more X-class flares. Other space weather around such major flaring adds at least as many grid disturbances as does major flaring.

The average cost to the U.S. economy of grid disturbances attributable - but not officially attributed - to relatively common solar activity is as high as \$4 billion/yr (Schrijver and Mitchell, 2012, subm.).

This impact occurs on top of market-price fluctuations associated with grid “congestion” that impact the US customers ($\gg \$100\text{M/y}$; Forbes & St. Cyr, 2002-2006).



<http://www.astro.gla.ac.uk/nam2010/pr15.php>



<http://fnetpublic.utk.edu/>

Conclusion: US grid disturbances

- The power grid disturbances studied by Schrijver and Mitchell (2012) are **generally not “catastrophic” and occur subject to non-extreme space weather conditions.**
- **The economic impact of grid disturbances alone is ten times the amount spent by NASA Heliophysics and NSF to study the phenomena from solar storms to geospace.**
- **The correlation of grid disturbances with major solar flaring reveals a weakness in the US power grid not recognized to date.**
- The cost of grid disturbances over the past two decades may be as high as \$40-80 billion dollars, much larger than the oft-cited Hydro-Quebec blackout in March, 1989, with an estimated impact of \$2 billion.
- Other phenomena associated with ‘every-day space weather’, i.e. not the extreme scenarios often quoted, add significantly to the economic impact. These include price variations in the electricity market, satellite anomalies and losses, and impacts on communications systems.
- All of these other impacts are yet to be quantified:

Economy of space weather

Most SWx impacts remain to be quantified in economic terms, while existing estimates need to be validated:

Category:	System:	Photons (X)(E)UV	Particles SEP, SPE, GLE, SCR, ...	Field+plasma wind, (I)CME
Satellite systems	General	Charging/Solar panel ESD & aging/orbit entry & decay	Extr.: SEU/Anomalies/Loss SEU/Anomalies/Loss	--
	Navigation (GNSS)	Scintillation/loss of lock	Extr.: SEU/Anomalies/Loss SEU/Anomalies/Loss	--
	Communication	Noise/limited propagation	Extr.: SEU/Anomalies/Loss SEU/Anomalies/Loss	--
	Surveillance/security	--	Extr.: SEU/Anomalies/Loss SEU/Anomalies/Loss	--
Conductor systems	Electric power grid	--	--	Outages by extreme GICs Grid PQ perturbations
	Pipelines	--	--	Corrosion shortening system life span
	Rail lines/ Communications cables	--	--	<u>Signaling problems</u>
Transportation system	Polar air routes	Flight rerouting	Fly-by-wire systems	Flight rerouting
	Air crew health	--	"We found no evidence that flight attendants are at increased risk of mortality from breast cancer or melanoma."	--

Economic impact: Not available Negligible effect \$Millions/y \$Billions/y \$Trillions/extreme event ?

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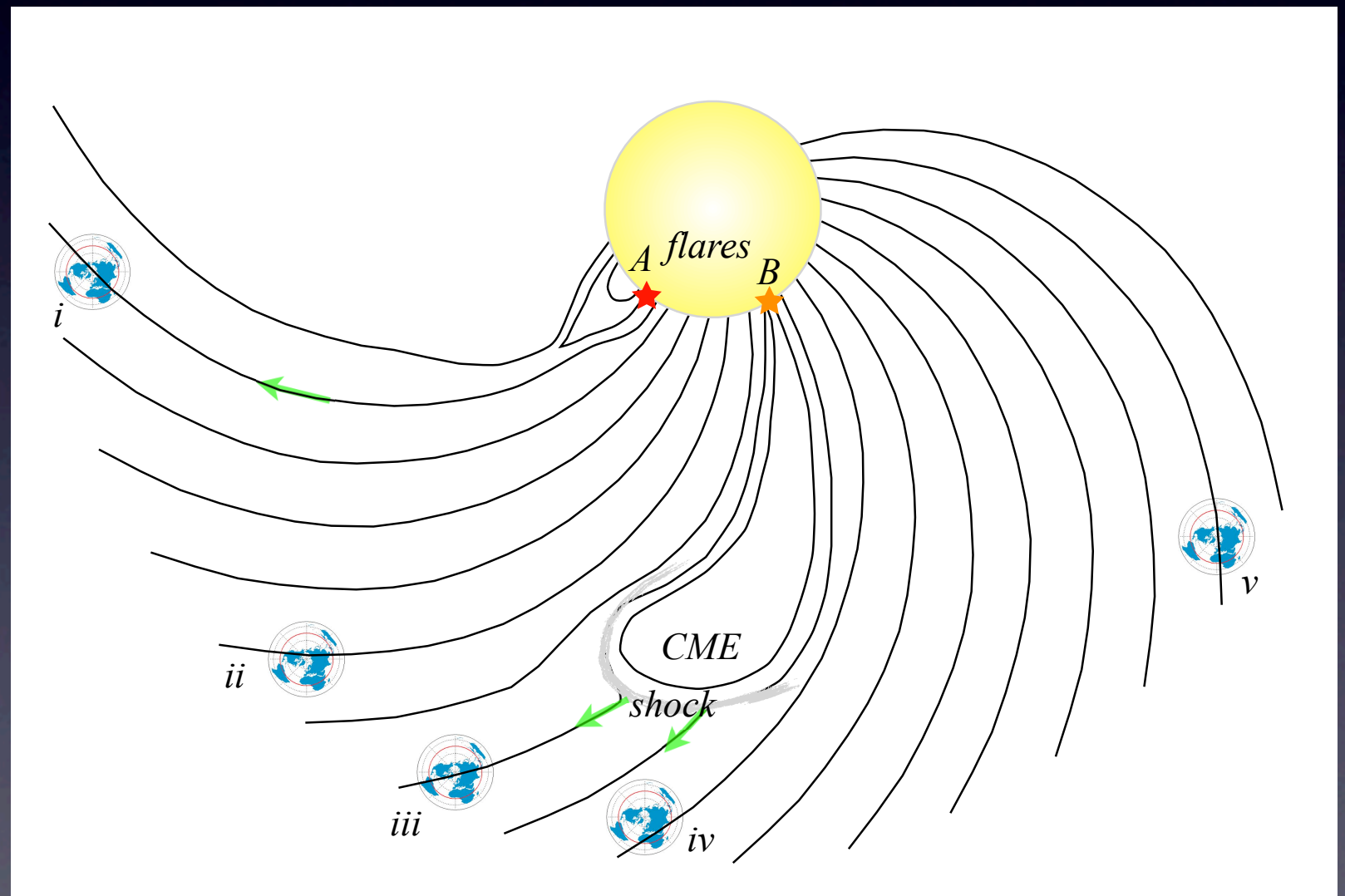
Estimating the frequency of extremely energetic solar events, based on solar, stellar, lunar, and terrestrial records

Or: how to determine statistics of rare solar events based on existing or obtainable records or models?

Karel Schrijver, Juerg Beer, Urs Baltensperger, Ed Cliver,
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Flares, coronal mass ejections (CMEs) and solar energetic particles (SEPs, SPEs, solar cosmic rays, ...)

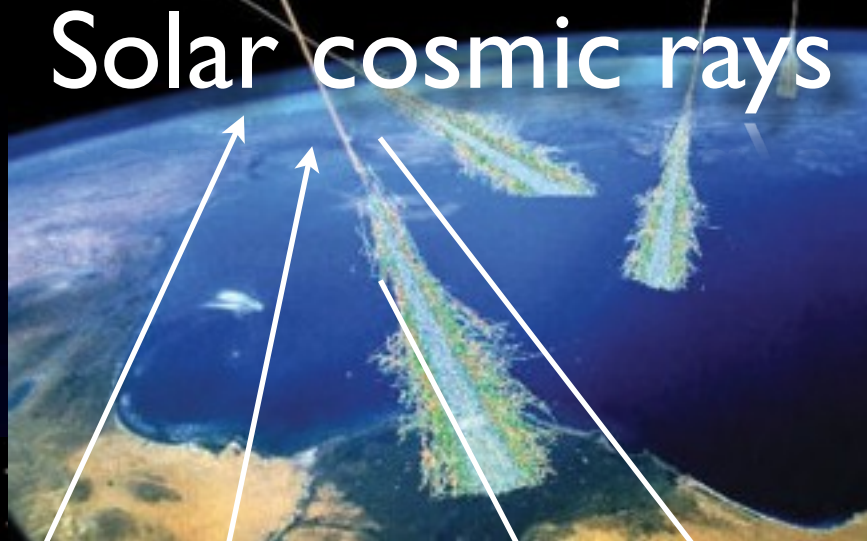
- Flares (X-rays, (E)UV, radio, + visible light): visible from the Earth-facing side of the Sun (i-v).
- CMEs: “halo-CME” directed towards Earth, and “glancing blows” (ii-iv)
- SEPs: sensible for events from solar central meridian to far side (i-iii), and after passage of Earth orbit (co-rotating interaction regions, CIRs; iv-v).



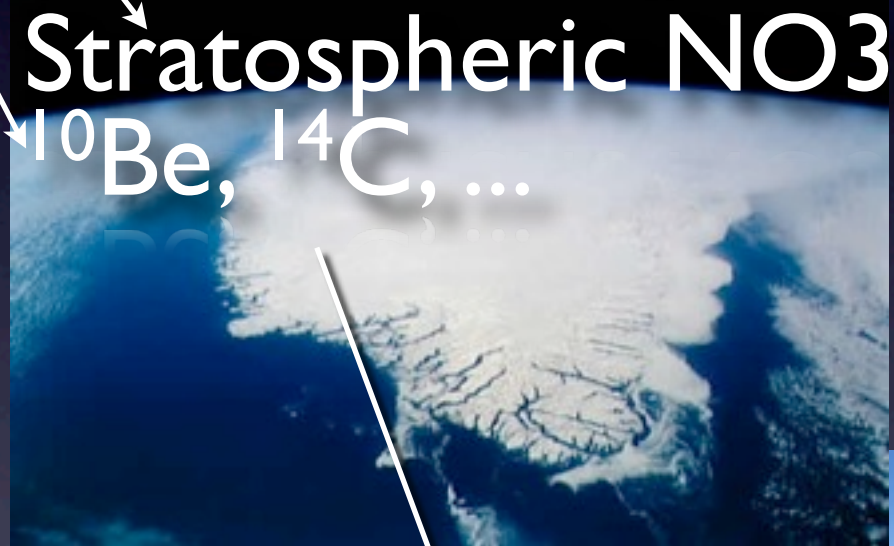
Pre-historic* records of solar activity

*Before ~1950

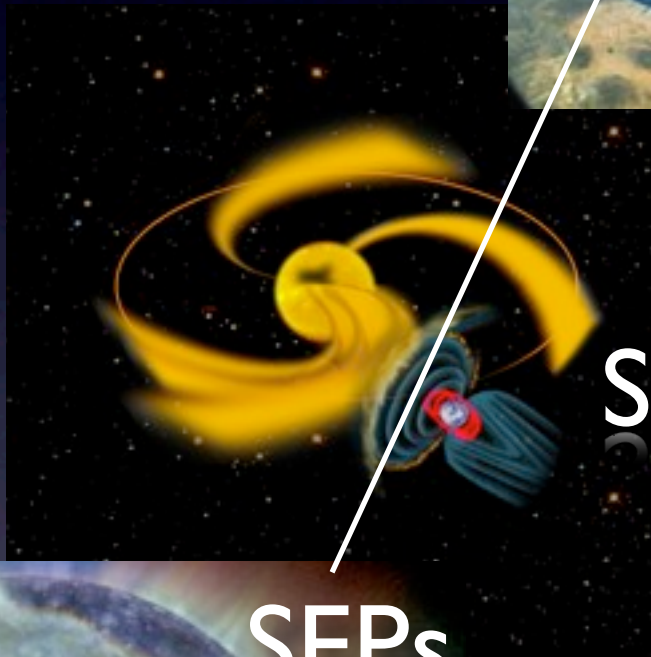
Solar cosmic rays



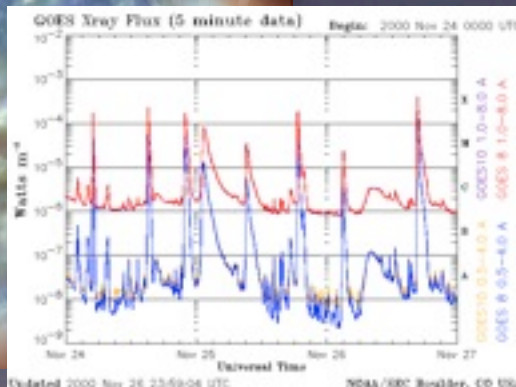
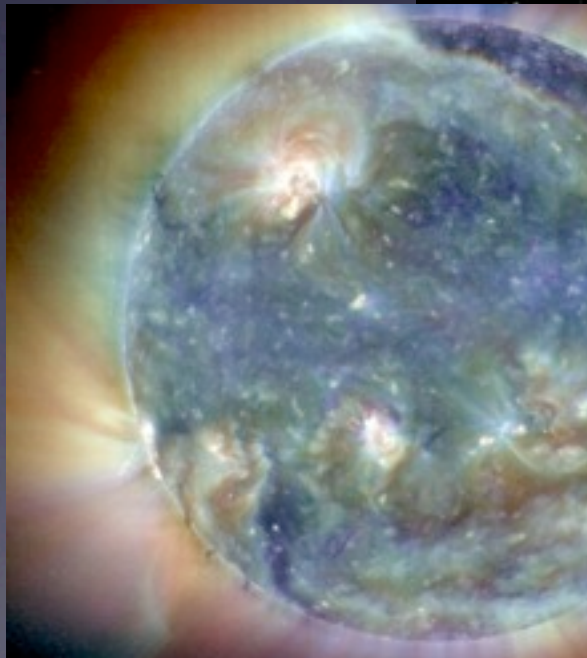
Stratospheric NO₃
¹⁰Be, ¹⁴C, ...



SEPs



SEPs
Flare



Ice cores:
chemicals,
radionuclides

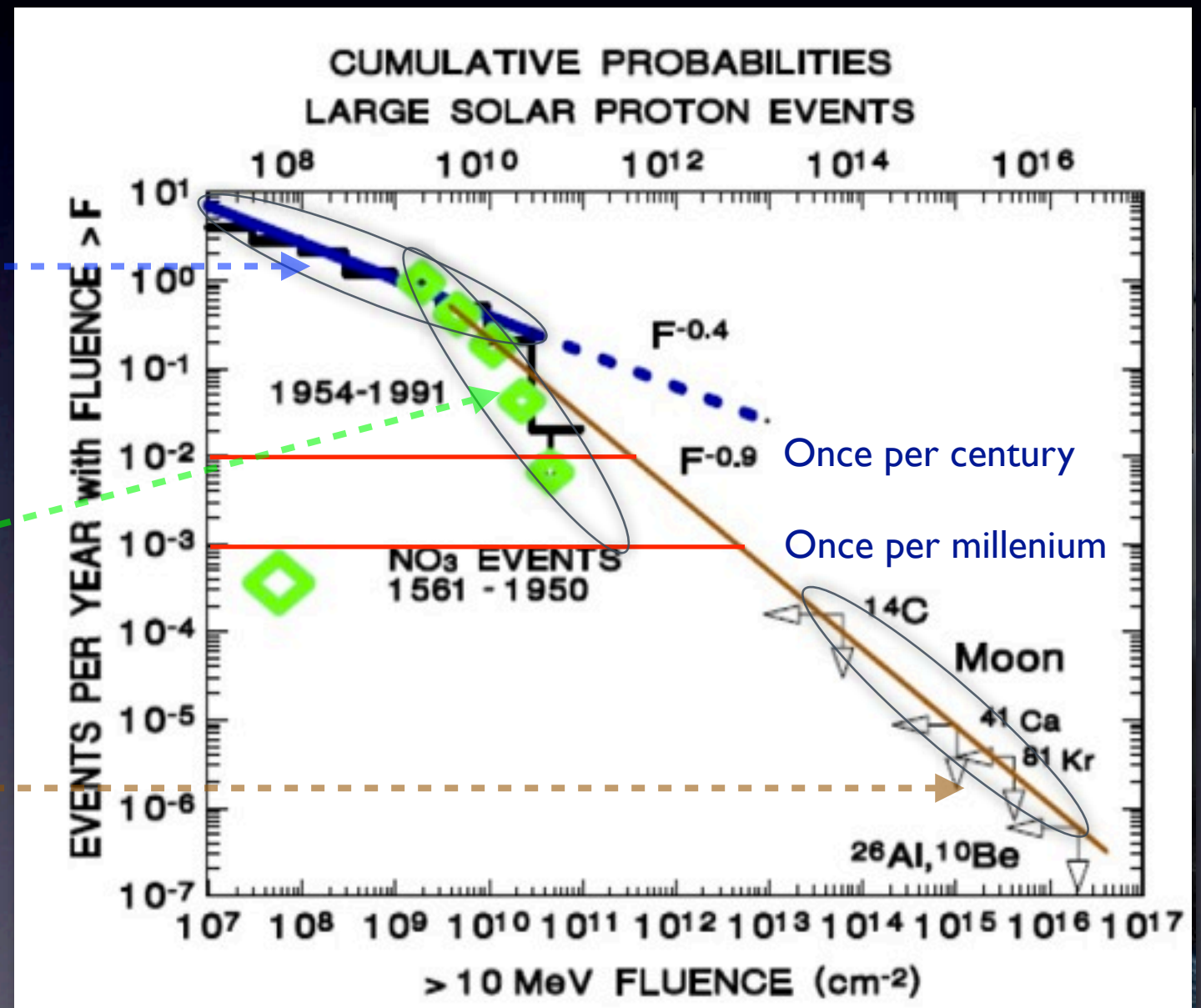


Solar energetic particles (SEPs)

SEP statistic can be obtained from:

- Spacecraft particle instruments and ground-based neutron monitors;
Records since ~1950s; too short
- Chemical signatures (NO₃ in ice)
Only one ice core published;
atmospheric scientists question pathways
- Radionuclides in biosphere, ice, rocks (Earth, Moon).

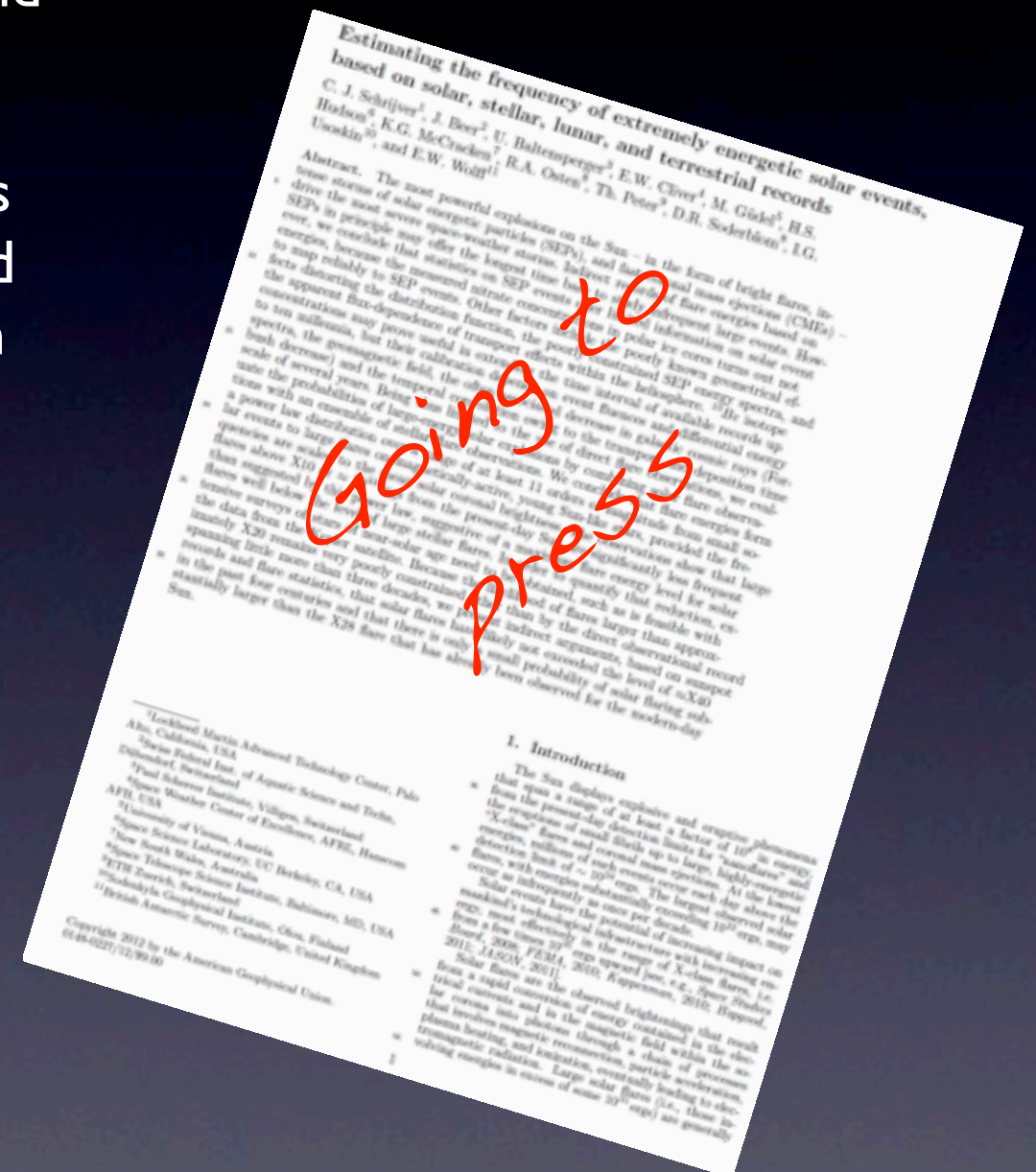
Lunar rocks: cumulative dose only.
Biosphere: washes out signal. Ice: limited resolution (~3y) on background of galactic cosmic rays.



ISSI* study team tasks

- Review statistics of direct observations of solar and stellar coronal magnetic storms.
- Establish cross-calibration of diagnostics in various wavelength bands (and their uncertainties) to yield distributions as a function of total energy for both solar and stellar data.
- Review statistics and significance of “geological” records of major coronal magnetic storms.
- Assess consistency of solar, stellar, and geological data and derive information on transport and impact processes from solar flares, through heliospheric ICMEs, to storage and analysis in, primarily, snow/ice deposits in polar regions.

* *International Space Science Institute, Bern, CH*



Going to
press

No, NO_3^- spikes in polar ice do not map usefully to strong SEP events

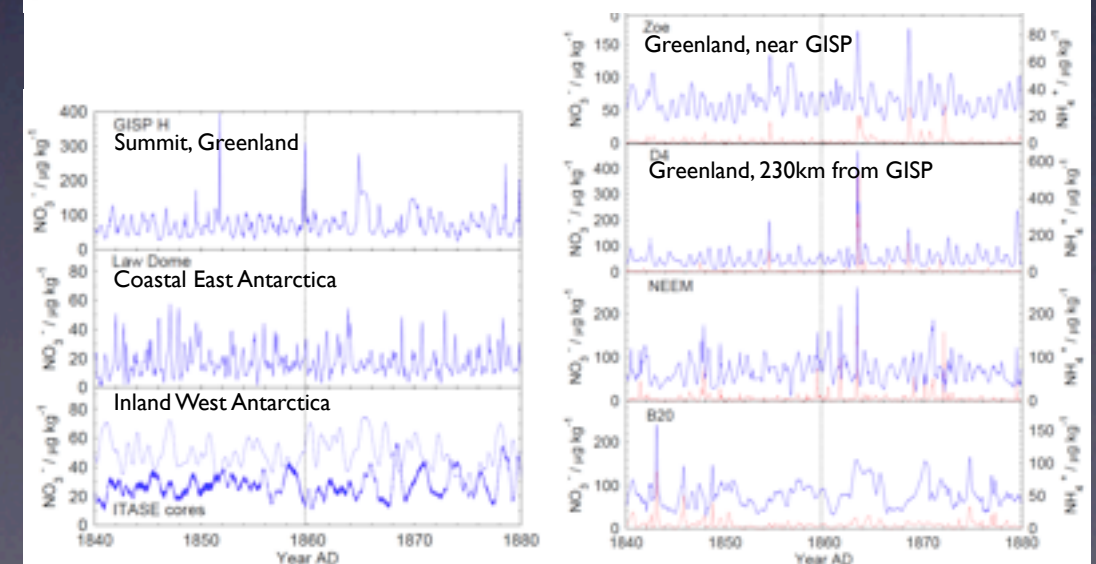
“The Carrington event not observed in most ice core nitrate records”
(to be[?] subm. to GRL)

E.W. Wolff, M. Bigler, M.A.J. Curran, J.E. Dibb, M.M. Frey I, M. Legrand
and J.R. McConnell

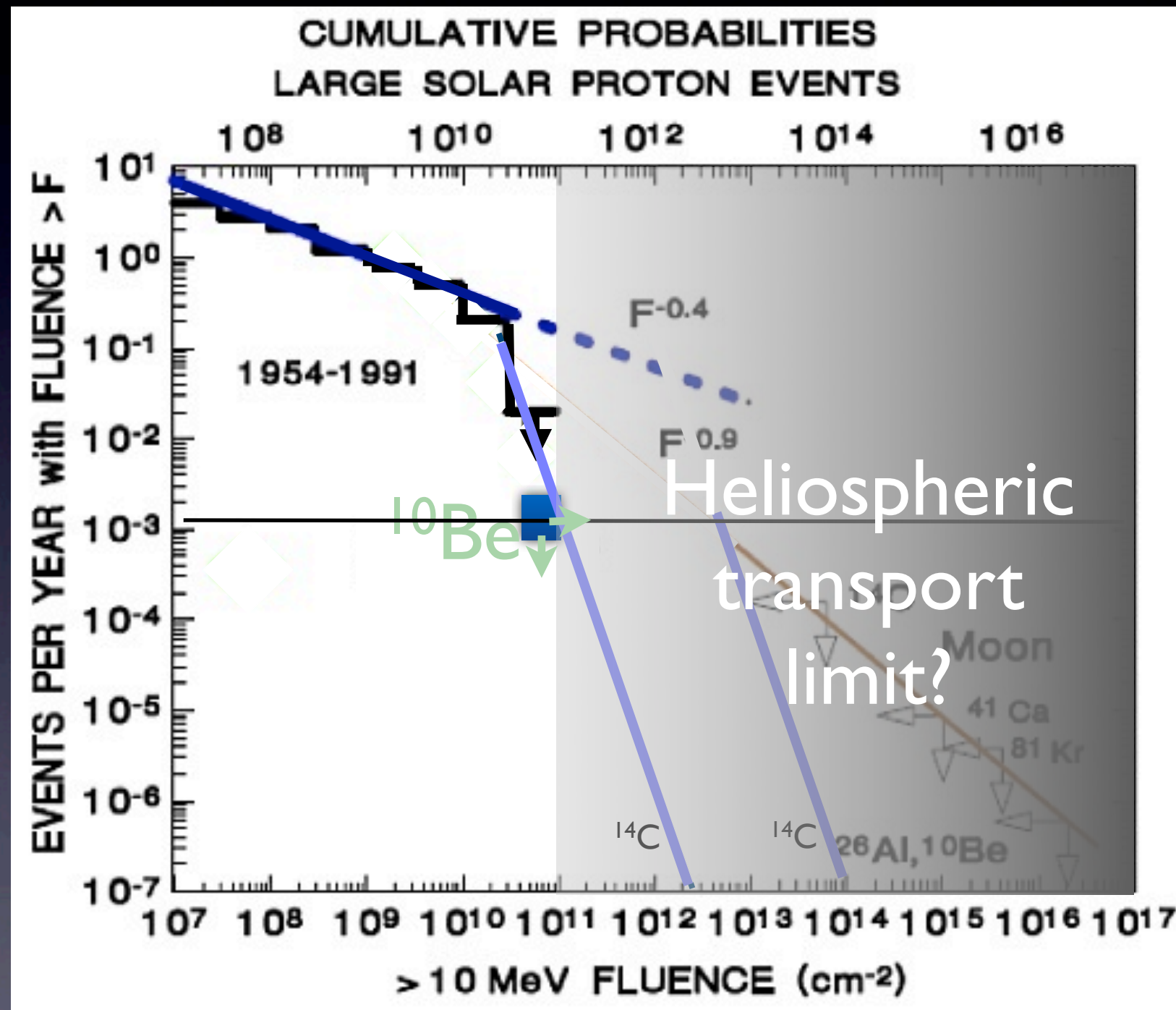
“It has been proposed that spikes in nitrate concentration in ice cores can be used to establish the statistics of past solar energetic particle events (SEPs). The Carrington Event of 1859 is often considered to be one of the largest SEPs of the last 150 years. Here we study multiple Antarctic and Greenland ice core records, and show that **only one out of 14 well-resolved (>10 samples/year) records has a nitrate spike claimed to be in 1859**, the year of the Carrington Event. **No sharp spikes are observed in the Antarctic cores studied here. In Greenland numerous spikes are observed in the 40 years surrounding 1859, but in cores where other chemistry was measured, all large spikes have the unequivocal signal, including co-located spikes in ammonium, formate, black carbon and vanillic acid, of biomass burning plumes.** It seems certain that most of the spikes in an earlier core, including the one claimed for 1859, are also due to biomass burning plumes. Taking all the cores together, it is clear that an event as large as the Carrington Event did not leave an observable and widespread imprint in nitrate in polar ice, and that **nitrate spikes cannot be used to derive the statistics of SEPs.**”

Table 1. Characteristics of the sites and ice cores used in this paper.

Core	Lat/ $^{\circ}$	Long/ $^{\circ}$	Acc rate/ cm $\text{H}_2\text{O a}^{-1}$	Period available	++	Resolution a^{-1}	Ref	Shown in figs?
Antarctic								
ITASE99-1	80.62S	122.62W	14	1707-1999	± 1	>10	1	
ITASE00-4	78.08S	120.08W	19	1798-2000	± 1	>10	1	
ITASE00-5	77.6S	123.99W	13	1736-2000	± 1	>10	1	Y
ITASE01-3	78.12S	95.65W	33	1858-2001	± 0	>10	1	
ITASE02-1	82.00S	110.01W	23	1790-2002	± 1	>10	1	Y
ITASE02-3	85.00S	105.00W	17	1848-2002	± 1	>10	1	
RIDS-A	78.73S	116.33W	22	1503-1995	*	>10	1	
Law Dome	66.78S	112.82E	70	1299-1996	± 0	~ 12	2	Y
Greenland								
GISP2 H	72.6N	38.5W	25	1561-1991	± 0	~ 15	3	Y
GISP2 B	72.6N	38.5W	25	818-1987	*	0.5	4	Y
Zoe, Summit	72.6N	38.3W	22	1840-1880	± 0	~ 20	#	Y
GRIP	72.56N	37.63W	~ 20	1767-1982	± 2	~ 4	5	Y
NGTB20	78.83N	36.50W	10	829-1994	± 5	~ 10	6	Y
NEEM	77.45N	51.06W	20	$<1840-2011$	$\pm 1^{**}$	~ 20	7, #	Y
D4	71.4N	44.0W	41	1788-2002	± 0	~ 40	8	Y

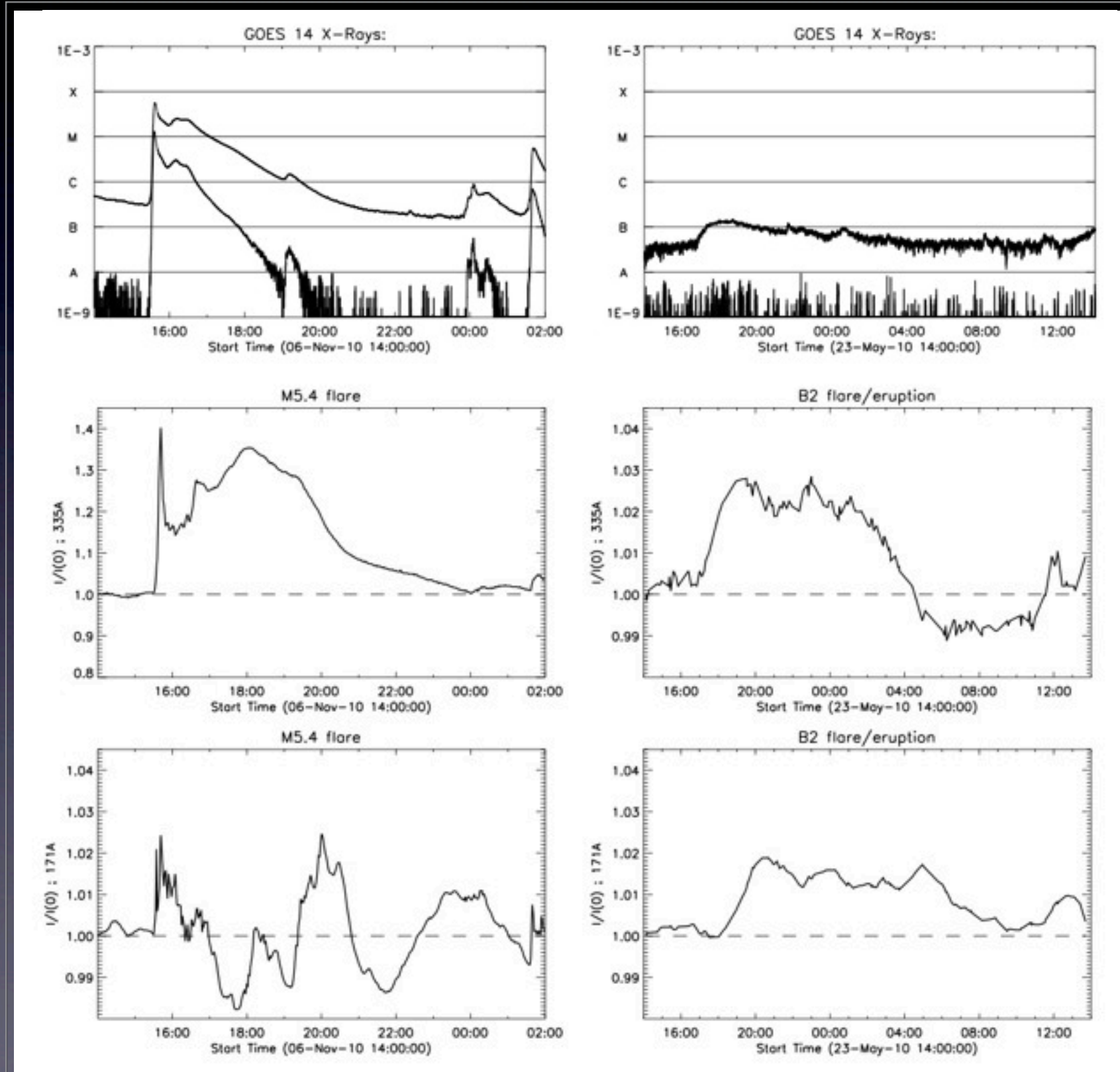


Revised SEP-event statistics after 1st ISSI meeting



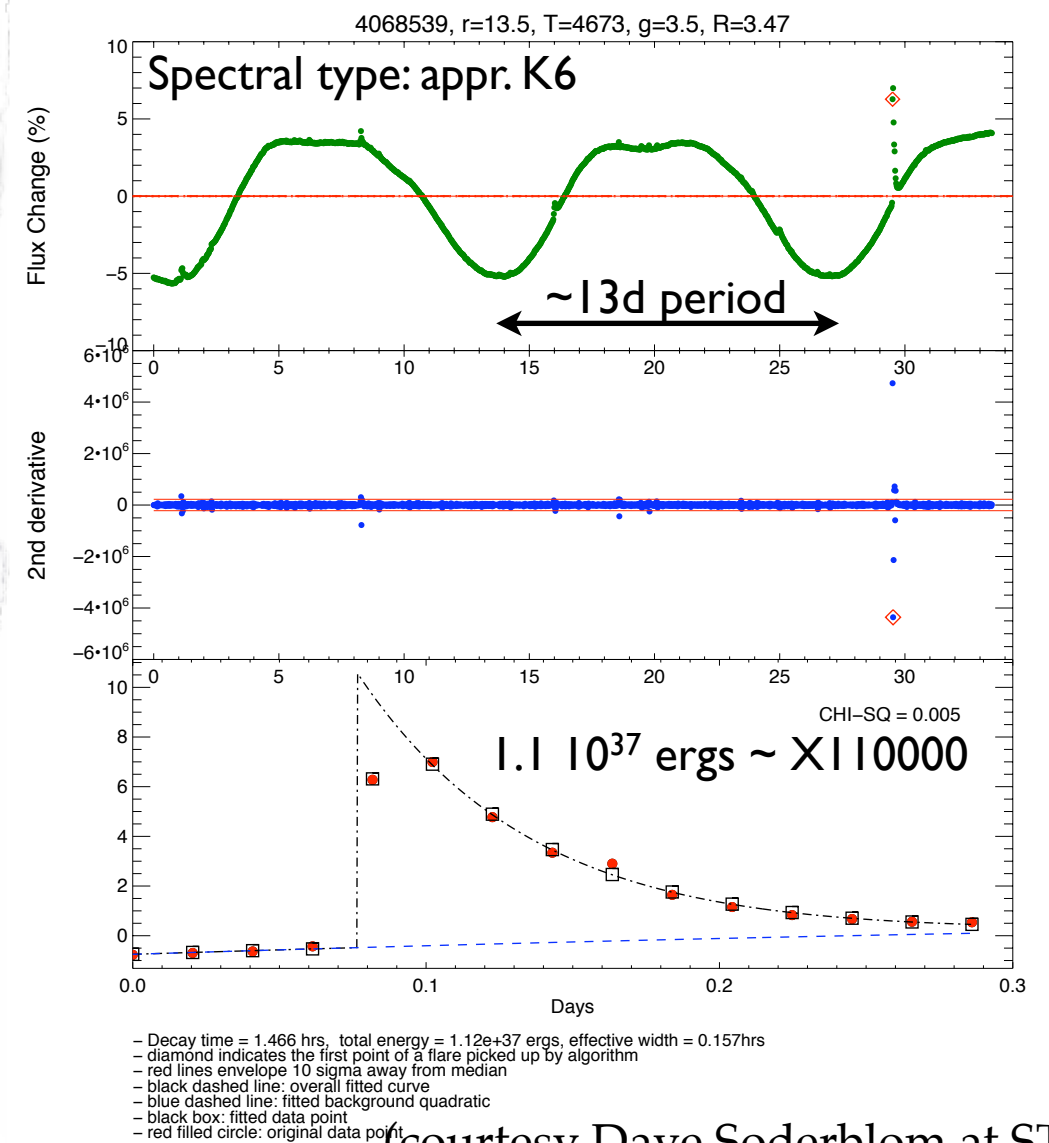
Chameleon behavior of solar storms: we cannot rely on a single proxy!

- GOES class provides a very uncertain measure of the energy in a solar coronal storm event.
- Example: GOES light curve peaks for an active-region flare and quiet-Sun filament eruption differ by factor of ~ 250 for comparable 'bolometric' energies in the X-ray/(E) UV domain.



Statistics of solar/stellar flares

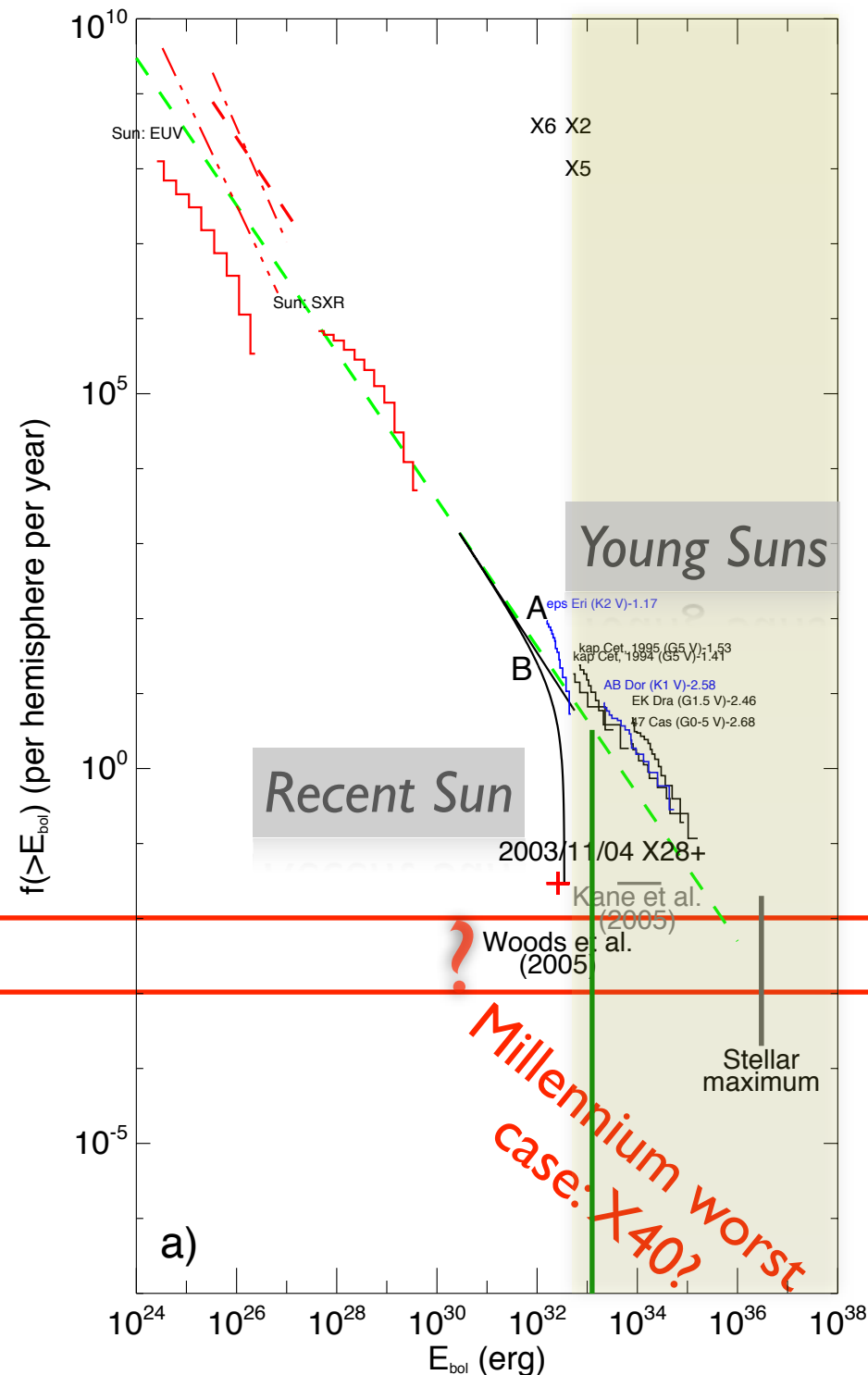
Kepler: monitoring 150,000 stars!



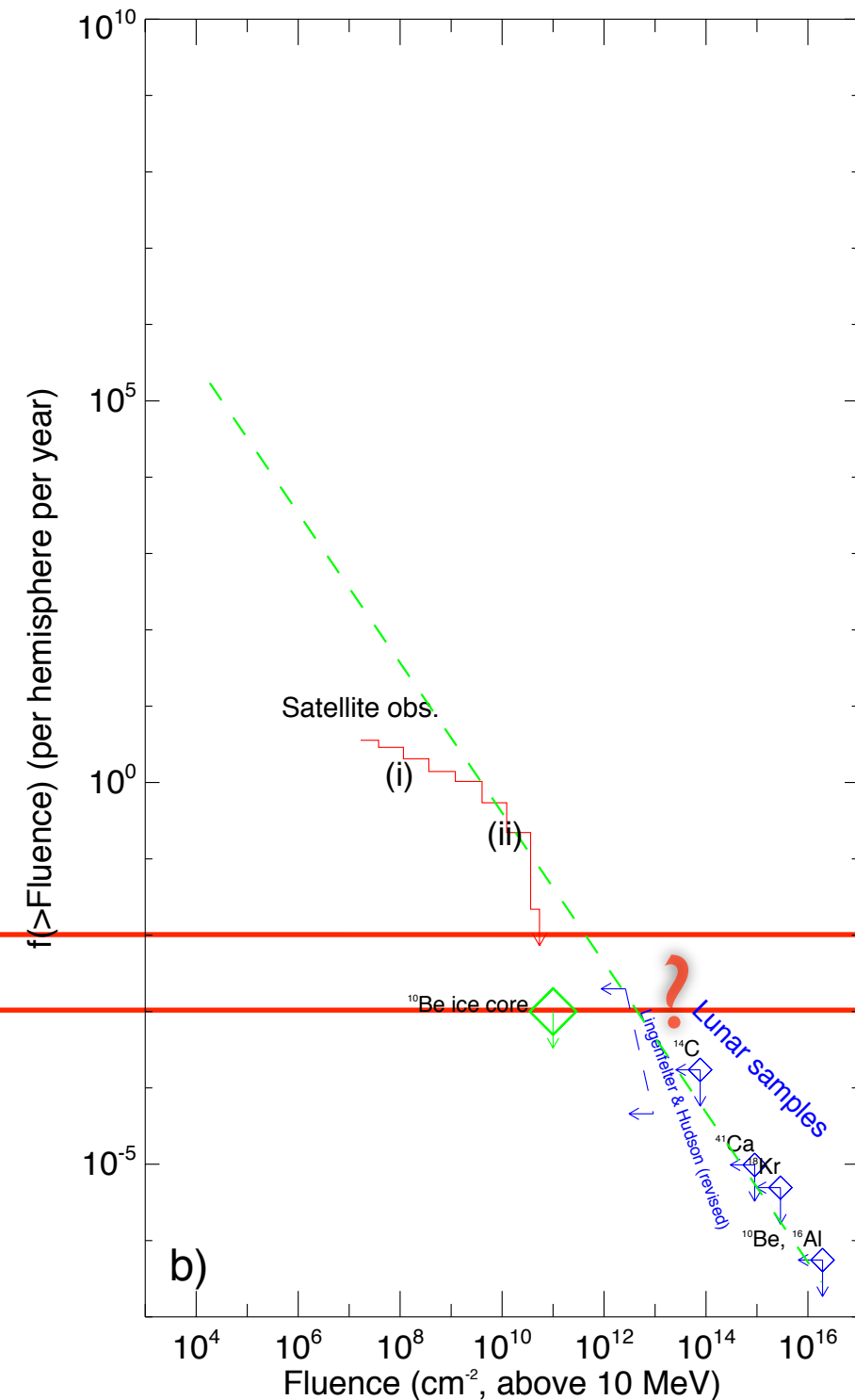
(courtesy Dave Soderblom at STScI)

Statistics of solar flares and SEP events

Flares



SEP events



Lessons learned ... so far

- If the largest flares follow a truncated power law - as suggested by limited solar & stellar data - then we can be 99% certain that flares larger than $\sim X36$ have not happened in past centuries*, and 99.9999% that flares larger than $\sim X39$ have not.
- The rarity of very large events requires that we combine data on one Sun with data on many Sun-like stars to validate the assumptions about infrequent events that yield the above upper limit on flare energy. Need to focus on stars of \sim solar age!
- This study could only be done by an interdisciplinary team: Sun-Stars-heliosphere-geospace-atmosphere-ice.
- This team has shown multiple “known facts” to be incorrect.

*That includes the 1859 Carrington events. From Cliver and Svalgaard (2005): "In this study we used the great solar-terrestrial disturbance of 1859 as a point of departure for an investigation of the limits of extreme space weather activity. We considered the various aspects of space weather disturbance: sudden ionospheric disturbance, solar energetic particles, solar wind, geomagnetic storm, and aurora. For each of these effects, we compiled (with varying degrees of completeness) size-ordered lists of the top events of the last ~ 150 years. We found that in each of these categories the 1859 event had close peers or superiors."

Society and Space Weather



<http://science.nasa.gov/media/medialibrary/2010/06/04/SpWeatherPoster1.jpg>

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Society and Space Weather



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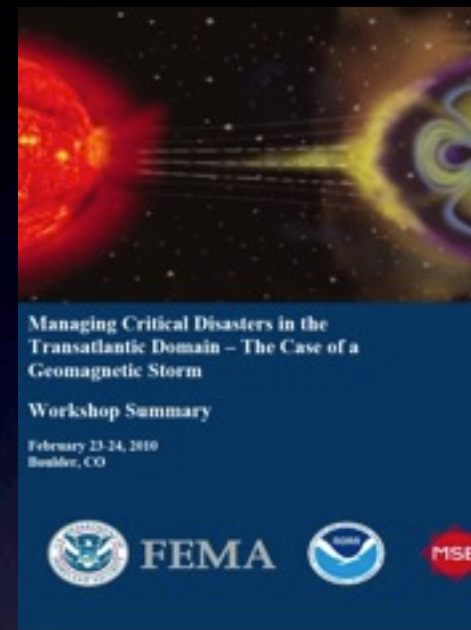
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Space-weather impact studies



"[...] an estimate of \$1 trillion to \$2 trillion during the first year alone was given for the societal and economic costs of a “severe geomagnetic storm scenario” with recovery times of 4 to 10 years."

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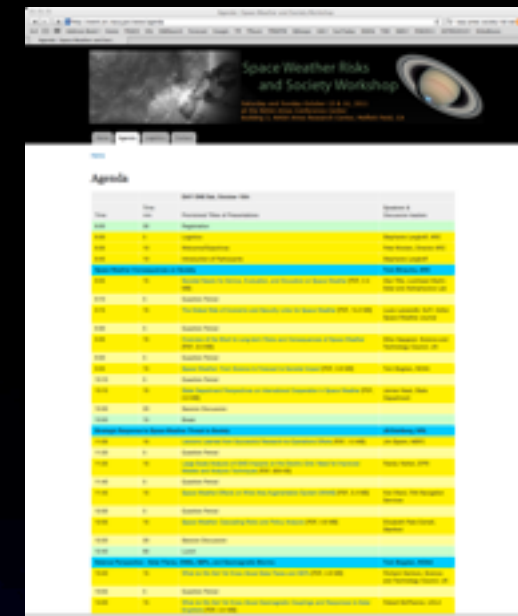
... one year ago:

- In media and in studies, the emphasis was on “extreme events” and “Doomsday scenarios”
- We could not find the expertise to assess the validity of these scenarios.
- So, we* invited experts ...

** Alan Title and Karel Schrijver @ LM, Mike Hapgood & Richard Harrison @ UK/STFC, Pete Worden and Stephanie Langhoff @ NASA/Ames, Tom Bogdan @ NOAA/SWPC*

Society and Space Weather Workshop

<http://event.arc.nasa.gov/sww/>



1	Allen, John	NASA Headquarters
2	Beer, Jürg	ETH Zurich
3	Blattnig, Steve	NASA Langley Research Center
4	Bloomfield, Shaun	Trinity College Dublin
5	Bogdan, Tom	National Oceanic and Atmospheric Administration
6	Bonadona, Michael	National Space Weather Program
7	Burkhard, Craig	Lockheed Martin Corporation
8	Chenette, David	Lockheed Martin Corporation
9	Dahlburg, Jill	Naval Research Laboratory
10	Daniels, Matt	NASA Ames Research Center
11	DeForest, Craig	Southwest Research Institute
12	Dischinger, Charles	NASA Engineering and Safety Center
13	Ferguson, Dale	Kirtland Airforce Base
14	Fisk, Lennard	University of Michigan
15	Fortuny, Joaquim	Center of the Protection and Security of the Citizen
16	Friend, Anita	UK Cabinet Office
17	Giampapa, Mark	National Solar Observatory
18	Guhathakurta, Madhulika	NASA Headquarters
19	Hapgood, Mike	UK: Science and Technology Facilities Council
20	Harrison, Richard	UK: Science and Technology Facilities Council
21	Hassler, Don	Southwest Research Institute
22	Head, James	U.S. Department of State
23	Holland, Mike	Allied Pilots Association
24	Horton, Randy	Electric Power Research Institute
25	Intriligator, Devrie	Carmel Research Center
26	Jaroux, BJ	NASA Ames Research Center
27	Johnson, Kenneth	Lockheed Martin Corporation
28	Jones, Bryn	SolarMetrics
29	Kappenman, John	Storm Analysis Consultants
30	Karcz, John	NASA Ames Research Center
31	Klupar, Pete	Space Systems Loral
32	Krause, Linda	NASA Marshall Space Flight Center
33	Kuznetsova, Masha	NASA Goddard Space Flight Center
34	Kwiatkowski, Stephen	Lockheed Martin Corporation
35	Langhoff, Stephanie	NASA Ames Research Center
36	Lanzerotti, Louis J	New Jersey Institute of Technology
37	Lauritis, Kristina	Lockheed Martin Corporation
38	Macalester, Mark	Federal Emergency Management Agency
39	Madden, John	Alaska Division of Homeland Security
40	Mannucci, Anthony	Jet Propulsion Laboratory
41	Mansour, Nagi	NASA Ames Research Center
42	Marnie, John	NASA Ames Research Center
43	McFee, Chris	UK: Government Office for Science
44	McGuirk, Michael	Massachusetts Institute of Technology
45	McPherron, Robert	University of California, Los Angeles
46	Mertens, Chris	NASA Langley Research Center
47	Morrison, Mons	Lockheed Martin Corporation
48	Nelson, Buddy	Lockheed Martin Corporation
49	Pate-Cornell, Elizabeth	Stanford University
50	Pedreiro, Nelson	Lockheed Martin Corporation
51	Pilcher, Carl	NASA Ames Research Center
52	Rees, John	UK: Natural Environment Research Council
53	Scargle, Jeffrey	NASA Ames Research Center
54	Schrijver, Karel	Lockheed Martin Solar and Astrophysics Laboratory
55	Sojka, Jan	Ural State University
56	Spann, James	NASA Marshall Space Flight Center
57	Straume, Tore	NASA Ames Research Center
58	Title, Alan	Lockheed Martin Solar and Astrophysics Laboratory
59	Tomczyk, Steven	National Center for Atmospheric Research
60	Turner, Ron	Homeland Security Studies and Analysis Institute
61	Wall, Mike	Space.com- reporter
62	Ward, Ken	Federal Aviation Administration
63	Washington, Kenneth	Lockheed Martin Corporation
64	Weston, Alan	NASA Ames Research Center
65	Wollack, Edward	NASA Goddard Space Flight Center
66	Worden, Pete	NASA Ames Research Center
67	Zeitlin, Cary	Southwest Research Institute

- 67 experts from a wide variety of international organizations, including FEMA, NEMA, DHS, State Dep., FAA, Air Force, Navy, NASA, US universities, electric power industry, UK Cabinet Office, Natural Environments Research Council, Science and Technology Facilities Council, EC Center for the Protection and Security of the Citizen.
- Attendees unanimously agreed that space weather presents a real and significant risk to society, and that the complex coupled systems involved from Sun to society requires a wide-ranging base of expertise to translate that threat into a quantified risk.
- Three aspects are unique to space weather: (1) synchronous impacts power, communications, and navigation systems, (2) impacts span one or more continents; (3) space-weather preparedness, response, and recovery are inherently international. These, and the need to engage subject matter experts with an exceptionally wide range of backgrounds, suggest the creation of a dedicated organization.

Space Weather Risks and Society

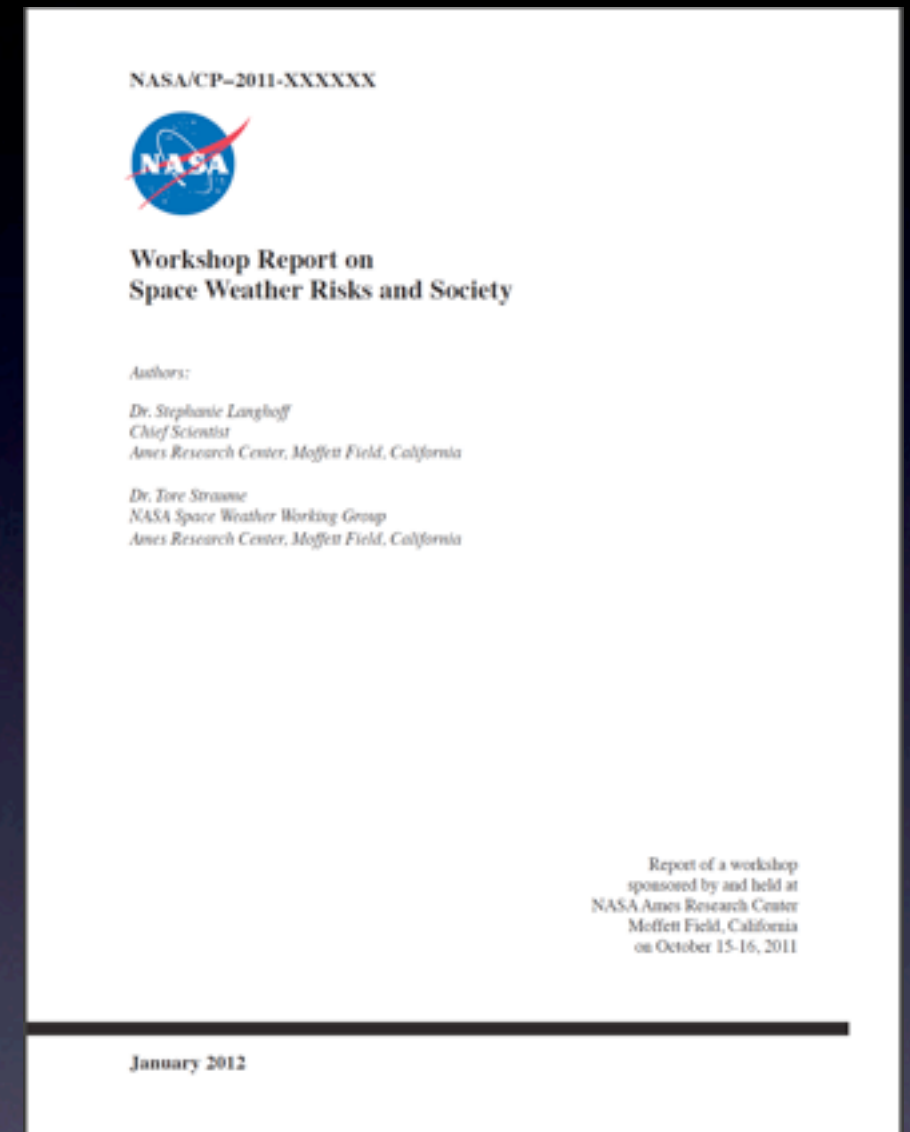
(NASA/Ames, October 2011)

“A weekend workshop entitled *Space Weather Risks and Society* was held at NASA Ames Research Center on October 15-16, 2011 to discuss humanity’s escalating susceptibility to space weather ...

The workshop participants unanimously agreed that the threat of space weather is real. The participants also resonated with a finding from the 2008 NRC report on a workshop on “Severe Space Weather Events” which stated that “... [...] A quantitative and comprehensive assessment of the societal and economic impacts of space weather will be a truly daunting task ...” One critical problem in that task formed one of the focus themes in the Ames workshop: how to bring together an interdisciplinary group of scientists, engineers, modelers, operators, societal leaders, emergency responders, etc., to make a quantitative and comprehensive assessment of the societal and economic impacts of severe space weather? ...

There was general agreement at the workshop that a [Society and Space Weather Institute] needed to be an interdisciplinary, independent, and international organization. It must be independent to bring our international partners in fully, and to provide independent and unbiased advice to policy makers. The SSWI needs to be interdisciplinary, because space weather crosses many disciplines. Finally, it needs to be international, because space weather has a large geographical footprint that crosses national boundaries. ...

The threat of space weather is real. It is not a question of ‘if’, but a question of ‘when’. We cannot be satisfied with status quo. A space weather calamity of epic proportions should not have to occur before we get the funds needed to protect our critical infrastructure. A relatively small investment in defining better the frequency of large space weather events and the impacts on our existing infrastructure would mitigate the potentially large downside risks that space weather poses for society. ...”



Space-Weather Awareness Dialogue

(EC/JRC Brussels; October 2011)

“In view of the risk of catastrophic technological failure and the upcoming solar maximum expected in early 2013, the European Commission’s Joint Research Centre together with the Directorate-General Enterprise and Industry organised a high-level ‘Space-Weather Awareness Dialogue’ in Brussels, Belgium, on 25-26 October 2011. ...

The Space-Weather Awareness Dialogue brought together about 70 high-level representatives ... In the course of the discussions **consensus was reached on the following points:**

- Space weather is a threat to our critical infrastructures that needs to be addressed.
- The analysis of the space-weather threat to ground-based critical infrastructure (power grid, aviation, telecommunications, etc.) is of equal importance as the study of space-based infrastructures.
- There is no central entity that takes the lead in the space-weather community.
- The assessment of space-weather impact on critical infrastructures requires a multidisciplinary effort from all stakeholders (scientists, engineers, infrastructure operators, policy makers).
- Ageing satellites that monitor space weather need to be replaced.
- A framework for better structured communication between the stakeholders is required.
- Open space-weather data sharing is necessary for improving early warning and impact models.
- While there is some preparedness for normal space weather in some infrastructure sectors, nobody is fully prepared for extreme events.
- The topic of space-weather impacts would benefit from cross-sectoral discussion.
- Emergency exercises could help raise awareness of space-weather impact.
- International cooperation is required to cope with the problem as response capabilities may be beyond the capacity of individual countries.

With respect to the many facets of the threat of space weather the JRC will continue and enhance its coordinating efforts and scientific activities.

The US proposal of a virtual institute on ‘Society and Space Weather’ will have to be assessed and a collaborative transatlantic approach for tackling both the space dimension and the critical-infrastructure dimension of space weather will be sought.”



SWx economic impacts largely unknown



Emphasis in government, academia, and media is on “High-Impact Low-Frequency” (HILF) events. Much more commonly occurring space weather impacts appear underappreciated: trans-disciplinary education and research is needed.

JRC Scientific and Technical Reports

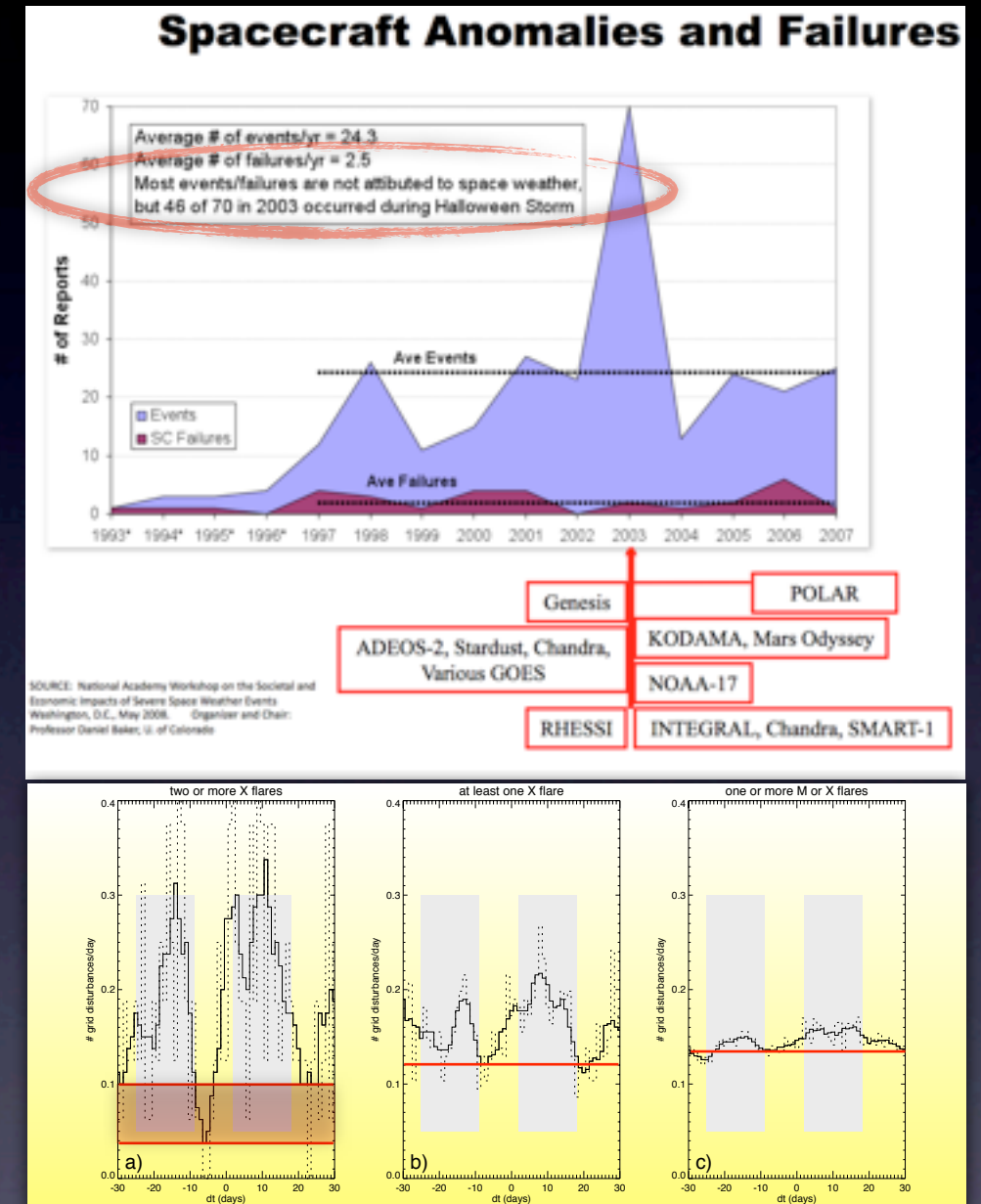
The Space-Weather Awareness Dialogue: Findings and Outlook

An event hosted by the European Commission's Joint Research Centre and co-hosted by the Directorate-General Enterprise and Industry
25-26 October, 2011, Brussels, Belgium
Elisabeth Krausmann

From the EC Space Weather Awareness Dialogue: “From the space-insurance perspective space weather is currently perceived a low concern with only few claims due to space-weather related damage. An explanation could be that anomalies may not have been claimed, as satellites have redundant systems, or that space weather was not recognised as the root cause of damage. During the severe space weather in 2003 reportedly 45 satellites were affected with 1 science satellite being a total loss. However, no claims were filed with the insurer. Generally, space insurance believes that preparedness levels are low. Satellites may have been designed to resist events of the magnitude of the 1989 and 2003 events but not for the 1921 or the 1859 Carrington event.”

EUR 25016 EN - 2011



The average cost to the U.S. economy of grid disturbances attributable - but not officially attributed - to relatively common solar activity is as high as \$4 billion/yr (Schrijver and Mitchell, 2012, subm.).

Economy of space weather

Most SWx impacts remain to be quantified in economic terms, while existing estimates need to be validated:

Category:	System:	Photons (X)(E)UV	Particles SEP, SPE, GLE, SCR, ...	Field+plasma wind, (I)CME
Satellite systems	General	Charging/Solar panel ESD & aging/orbit entry & decay	Extr.: SEU/Anomalies/Loss SEU/Anomalies/Loss	--
	Navigation (GNSS)	Scintillation/loss of lock	Extr.: SEU/Anomalies/Loss SEU/Anomalies/Loss	--
	Communication	Noise/limited propagation	Extr.: SEU/Anomalies/Loss SEU/Anomalies/Loss	--
	Surveillance/security	--	Extr.: SEU/Anomalies/Loss SEU/Anomalies/Loss	--
Conductor systems	Electric power grid	--	--	Outages by extreme GICs Grid PQ perturbations
	Pipelines	--	--	Corrosion shortening system life span
	Rail lines/ Communications cables	--	--	<u>Signaling problems</u>
Transportation system	Polar air routes	Flight rerouting	Fly-by-wire systems	Flight rerouting
	Air crew health	--	"We found no evidence that flight attendants are at increased risk of mortality from breast cancer or melanoma."	--

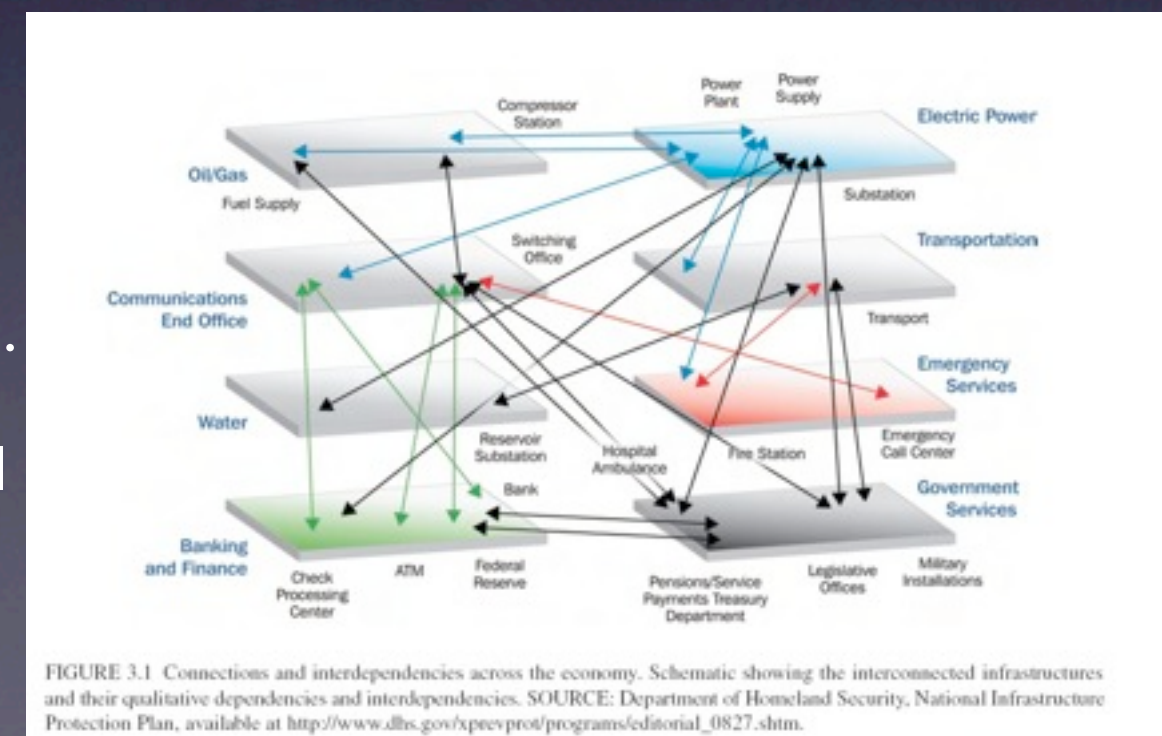
Economic impact: Not available Negligible effect \$Millions/y \$Billions/y \$Trillions/extreme event ?

SWx: unique attributes

- Affects communication, navigation, & electrical power grid in space and on the ground near-synchronously
- Impacts span continent(s) and thus transcend scales of 'classical' events
- Consequences are international; preparations, mitigation, response and recovery require international coordination

SWx: susceptibility creep

- Increasing dependence on space-based assets (B\$150+ of space assets)
- Increasing loads on continent-wide power grid (210,000+ miles of high-voltage lines in the US).
- Increasingly complex and coupled technological networks.



... now, one year later:

- We may have evidence that extreme solar events are no more extreme than what we have already experienced.
- We know that the susceptibility of our technological infrastructure is MUCH larger than we realized, with costs of billions each year in grid disturbances alone.
- We need to understand how to protect ourselves from the common as well as from the extreme, even as our technological infrastructure grows more susceptible and coupled.
- The investment needed to follow the path from space weather into society is expected to quickly pay for itself.

